Repeater Production for the North Atlantic Link

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(Manuscript received September 20, 1956)

Production of submarine telephone cable repeaters, designed to have a minimum trouble-free life of twenty years, required many new and refined manufacturing procedures. Care in the selection and training of personnel, manufacturing environment, inspection, and testing, were of great importance in the successful attainment of the ultimate objective. Although quality af praduct has always been of major significance in Western Electric Company manufacture, building electronic equipment for use at the bottom of the ocean, where maintenance is impossible and replacement af apparatus extremely expensive, required unusual manufacturing methads.

MANUFACTURING OBJECTIVE

Late in 1952, the manufacture of flexible repeaters for the North Atlantic Link of the transatlantic submarine telephone cable system was allocated to the Kearny Works of Western Electric Company.

In accordance with established practice in initiating radically new products and processes, production of these repeaters was assigned to the Engineer of Manufacture Organization rather than to regular manufacture in the telephone apparatus shops. The job — to produce 122 thirty-six channel carrier repeaters and 19 equalizers capable of operating satisfactorily at pressures up to 6,800 pounds per square inch on the ocean floor, with minimum maintenance, for a period of at least twenty years. Initial delivery of repeaters was required for March, 1954, less than a year and a half after the project started.

GENERAL PHILOSOPHY

Quality has always been the prime consideration in producing apparatus and equipment for the Bell System. There is an economical breaking point, however, beyond which the return does not warrant the abnormal

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expenditures required to approach theoretical perfection. The same philosophy applies to all manufactured commodities, be they automobiles, airplanes or telephone systems. In general, all of these products are physically available for preventive and corrective maintenance at nominal cost. With electronic repeaters at the bottom of the ocean, maintenance is impossible and replacement would be extremely expensive.

The general philosophy adopted at the inception of the project was to build integrity into the product to the limit of practicability. To do this, a number of fundamental premises were established, which form the foundation of all operations involved:

1. Manufacturing environment would be provided which, in addition to furnishing a desirable place to work, could be kept scrupulously clean and free from contamination.

2. The best available talent would be screened and selected for the particular work involved.

3. Wage payments would be based on day work, rather than on an incentive plan basis, because production schedules and the complexity of the operations did not permit the high degree of standardization essential to effective wage incentive operation.

4. A sense of individual responsibility would be inculcated in every person on the job.

5. Training programs would be established to thoroughly prepare supervisors, operators, and inspectors for their respective assignments before doing any work on the project.

6. Inspection, on a 100 per cent basis, would be established at every point in the process which could, conceivably, contribute to, or affect the integrity of the product.

PREPARATION FOR MANUFACTURE

Manufacturing Location

It appeared desirable to set up manufacture in a location apart from the general manufacturing area. Experience gained to date has satisfied us that this was the correct approach, since it provided a number of advantages:

1. Administration has been greatly facilitated by having all necessary levels of supervision located in the immediate vicinity of the work.

2. It was necessary for the people on the job to acquire and maintain a new philosophy of perfection in product, rather than a high output at an "acceptable quality level." This was easier at a separate location, since only one philosophy was followed throughout the plant.

3. Engineering, production control, service and maintenance organizations were located close to actual production and had no assignments other than the project.

4. The small plant, due to its semi-isolation, tends to produce a very closely knit organization and good teamwork.

A large number of manufacturing locations were examined and the one selected was a one-story modern structure in Hillside, New Jersey, which provided a gross area of 43,700 square feet.

The entire plant was air conditioned; in most cases, the temperature was controlled to minimum 73 degrees F, maximum 77 degrees F. The air was filtered through two mechanical and one electrostatic filters. Relative humidity was maintained at maximum 40 per cent in all but one area — the capacitor winding room — in which it was necessary to maintain maximum 20 per cent humidity to avoid mechanical difficulty with capacitor paper. While most of the air was recirculated, the air from the cafeteria, cleaning room, locker and toilet rooms was exhausted to the

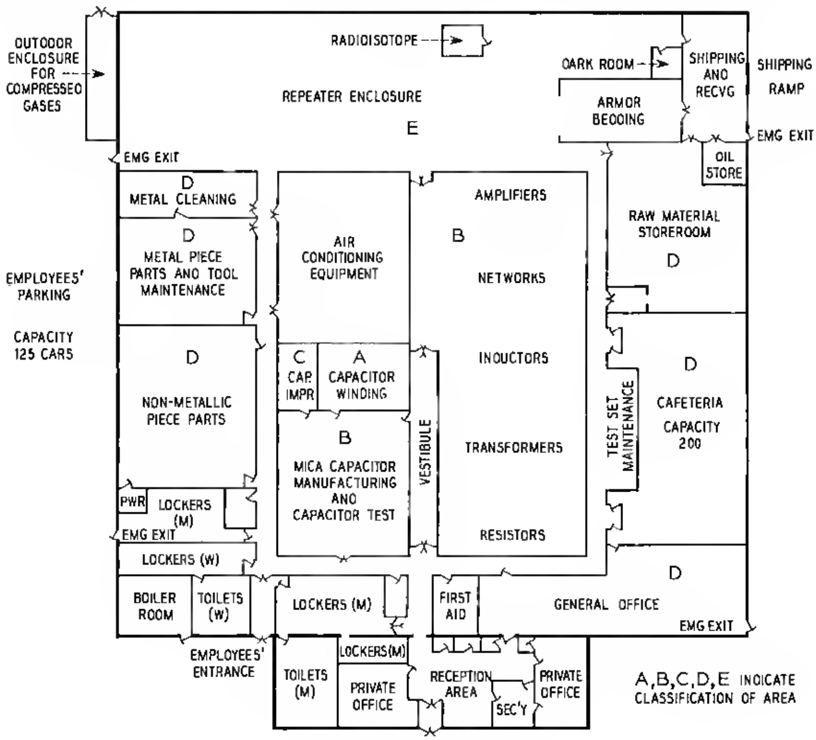


Fig. 1 — Plant layout.

outside atmosphere. Two separate air conditioning systems were in use. One, of 300 tons capacity, provided for most of the plant, while a smaller unit of 30 tons capacity served the capacitor winding, testing, and impregnating rooms. Each installation had its own air filtering and conditioning equipment.

Plant Layout

The plant layout is illustrated in Fig. 1. All working areas, with the exception of the repeater enclosure area, were individually enclosed, and walls from approximately four feet ahove the floor were almost entirely of reinforced glass. This arrangment facilitated supervision hy other than first-line supervisors, who were located with the groups, and provided a means of viewing the operations by the many visitors at Hillside, without contaminating the critical areas or disturbing the operators.

Analysis of Design for Facilities and Operations

In analyzing the design for manufacture there were, of course, numerous instances where conventional methods and facilities were entirely adequate for the joh. Since their inclusion would contribute little to this article, we shall confine the description to those cases which are new or unusual.

Collaboration with Bell Telephone Laboratories in Preparation of Manufactoring Information

Early in 1953 a coordination committee was estahlished, consisting of representatives from the various Lahoratories design groups and Western engineers, which met on a bi-weekly hasis during the entire period preceding initial manufacturing operations. These meetings provided a clearing house for questions and policies of a general nature for this particular project and served to keep all concerned informed as to the progress of design and the preparations for manufacture.

It is customary, during the latter stages of development of any project at the Lahoratories, for Western engineers to participate in the preparation of manufacturing information as an aid in pointing the design toward the most economical and satisfactory production methods and facilities. Since the decision to use the Bell System repeater in the Transatlantic system was hased on the performance of the Key West-Havana installation, and the fact that changes in design would require further

trials over an extended period of time, only minor changes to facilitate manufacture were made. Further, since some experience had been gained by the Laboratories in producing repeaters for that installation, it was decided to "pool" effort in preparing the manufacturing process information, which is normally Western's responsibility. Close cooperation of the two groups, therefore, has resulted in the production of repeaters which are essentially replicas of those in the initial installation except for the internal changes necessary to increase transmission capacity from 24 to 36 channels.

Other Western Electric Locations and Outside Suppliers

During the development work on the Key West-Havana repeaters, the Hawthorne Works of Western Electric had furnished the molybdenum-permalloy cores for certain inductors, the Tonawanda Plant had furnished mandrelated resistance wire, and the Allentown Plant had fabricated the glass seal subassemblies. Since the experience gained in this development work was extremely valuable in producing the additional material required for the Transatlantic system and since the facilities for doing the work were largely available, these various locations were asked to furnish similar material for the project. Although the Kearny Crystal Shop had not been involved in the Key West-Havana project, arrangements were made there to make the crystals for this project, since facilities were available, along with considerable experience in producing precision units.

Subcontracted Operations

While it was believed, initially, that all component parts for repeaters should be manufactured by Western Electric, critical analysis indicated that it was neither desirable nor economical in certain cases. One of the outstanding examples in this category is the hardened and ground chrome-molybdenum steel rings that constitute the strength members in the repeater and sustain the pressures developed on the ocean bottom. Purchasing the many large and varied machine tools and associated heat treating equipment necessary to produce these parts would have required a substantial capital expenditure and additional manufacturing space. Arrangements, therefore, were made with a highly qualified and well equipped supplier to produce the rings, using material furnished by Western, which had been previously inspected and tested to very stringent requirements.

The situation attending the manufacture of a relatively small numher of comparatively large copper parts used in the rubher and core tuhe seals was much the same. Here, again, the large size machine tools and additional manufacturing space, required for only a short time, would have increased the over-all cost of the project considerably. These parts, therefore, were suhcontracted in the local area and inspection was performed hy Hillside inspectors.

A safeguard, in so far as integrity is concerned, was provided by the fact that these were individual parts that could be reinspected at the time of delivery. No subassembly operations that might possibly result in oversight of a defect, were suhcontracted.

Manufacturing Conditions

Two major problems confronted us in planning the manufacture of repeaters. First, to produce units that were essentially perfect; and second, to prevent the contamination of the product hy any substance that might degrade its performance over a long period of time. In approaching both of these objectives, it was realized that the product had a definite economic value which the cost of production should not exceed. In many cases, therefore, it was necessary to rely on judgment, backed by considerable manufacturing experience, in determining when the "point of no return" had been reached in refining processes and practices.

The initial approach to this phase of the job was to classify, with the collahoration of Bell Telephone Laboratories, all of the manufacturing operations involved as to the degree of cleanliness required. In setting up these criteria, it was necessary to evaluate the importance of contamination in each area and the practicahility of eliminating it at the source or to insure that whatever foreign material accumulated on the product was removed.

A representative case is the machining of piece parts. While the shop area is cleaner, perhaps, than any similar area in industry, the very nature of the work is such that immediate contamination cannot he avoided since material is being removed in the form of chips and turnings, and a water soluble oil is used as a coolant. In this instance, however, the parts can be thoroughly cleaued and their condition ohserved before leaving the area. Conversely, iu the case of an operation such as the assembly of paper capacitors into a container which is then hermetically sealed, it is vitally necessary to insure that both the manufacturing

area and the processes are free from, and not conducive to producing, particles of material which are capable of causing trouble.

The various classifications established for the production areas include specific requirements as to temperature, relative humidity, static pressure with respect to adjacent areas, cleanliness in terms of restrictions on smoking and the use of cosmetics and food, and the type and use of special clothing.

Special Clothing

Employees' clothing was considered one of the most important sources of contamination for two reasons; first, for the foreign material that could be collected upon it and carried into the manufacturing areas, and second, that various types of textiles in popular use are subject to considerable raveling and fraying.

After considerable study of many types of clothing for use in critical areas, the material adopted was closely woven Orlon, which has proved to be acceptably lint-free. The complete uniform — supplied at no cost to employees — consists of slacks and shirts for both male and female employees, Orlon surgeon's caps for the men and nylon-visored caps for the women. In addition shoes, without toecap seams, were provided. Nylon smocks were furnished to protect the uniforms while employees moved from locker rooms to the entrance vestibule. Two changes of clothing were provided each week, and the laundering was done by an outside concern.

Employees to whom this special clothing was issued were paired for locker use. Both kept their uniforms and special shoes in one locker and their own clothes and shoes in the other. This prevented the transfer to the uniforms of any foreign material that might exist on the street clothing. At the entrance vestibule to the A, B, and C areas (Fig. 1) the employees were required to clean their shoes in the specially designed facilities provided and to wash their hands in the wash basins installed for this purpose. Smocks were then removed and hung on numbered hooks that line the walls at the end of the vestibule. Employees were then permitted to go to their work positions within the inner areas. At any time that it was necessary for employees to leave the work areas for any purpose, they were required to put on their smocks in the vestibule and upon their return, to go through the cleaning procedure again.

Employees in the other areas were provided only with smocks, mainly for the protection of their clothes since the work involved could soil or stain them but could not be contaminated from the clothing.

Cleaning

Schedules were established for cleaning the areas at regular intervals, the frequency and methods depending upon the type of manufacturing operations and the activity. Usually, the vinyl plastic floors were machine scrubbed and vacuum dried. Walls, windows and ceilings were cleaned by hand with lint-free cloths. Manufacturing facilities such as bench tops, which were linoleum covered, were washed daily. Test sets, cabinets, test chambers and bench fixtures were also cleaned daily. Hand tools were cleaned at least once a week by scrubbing with a solution of green soap, rinsing in distilled water, followed by alcohol and then dried in an oven.

Dust Count

Since it was impossible to determine what contaminating material in the form of air-borne particles might be encountered from day to day, and what the effect might be during the life of the repeaters, the general approach to this problem was to control, so far as possible, the amount of dust within the plant.

In order to verify, continuously, the over-all effectiveness of the various preventive measures, dust counts were made in each classified area at daily intervals, using a Bausch and Lomb Dust Counter. This device combines, in one instrument, air-sampling means and a particle-counting microscope. Over a two-year period it has been possible to maintain, in certain areas, a maximum dust count of between 2,000 and 3,500 particles per cubic foot of air with a maximum size of 10 microns. Control checks, taken outside the building at the employees' entrance, generally run upwards of 25,000 particles per cubic foot, a good portion of which are of comparatively large size.

PRODUCTION AND PERSONNEL

Equipping the plant, obtaining and installing facilities, and selecting and training personnel proceeded on a closely overlapped basis with receipt and analysis of Bell Telephone Laboratories' product design information. Because of the critical nature of the product, provisions were made not only for the most reliable commercially available utilities and services, but also for emergency lighting service in some areas. Maintenance and service staffs had to be built up rapidly as the supervisory and manufacturing forces were being developed.

"Qualification" of All Personnel

Before employees were assigned to production work they were required to pass a qualification test established by the inspection organization to demonstrate satisfactory performance. Programs were, therefore, set up for "vestibule" training and qualification of new employees. This activity was carried on by full-time instructors who had been trained by Western and Bell Laboratories engineers. Training was carried out in two stages:

1. (a) The employee received instruction and became acquainted with equipment and requirements. (b) A practice period in which the employee developed techniques and worked under actual operating conditions, with all work submitted to regular inspection.

2. A qualification period in which the employee was required to demonstrate that work satisfactory for project use could be produced.

The main objective during stage 1 was progressive quality improvement and in stage 2 the maintenance of a satisfactory quality level over an extended period of time. Employees made a definite number of units at acceptable quality levels in order to qualify. The number of units required for training varied with the type of work and the ease with which it was mastered.

All personnel were required to pass qualification tests before being assigned to production work and were restricted to that work unless trained and qualified for other work. Employees trained on more than one job were requalified before being returned to a previous assignment.

Records of the performance of individual operators started in the training stage were continued after the employees were assigned to production work. The performance record of the operators was based on results obtained during the inspection of their work, while that of the inspectors was based on special quality accuracy checks of their work.

Personnel Selection

It was apparent that the new manufacturing techniques, including the cleanliness and quality demands, would necessitate that all shop supervisors and employees be very carefully selected. It also appeared (and this was subsequently confirmed) that after the careful selection and training of supervisors, long training periods would be required for specially selected shop employees.

In selecting first line shop supervisors, such factors as adaptability, personality, and ability to work closely with the engineers were of paramount importance. For the parts and apparatus included in their re-

sponsibility, they were required to thoroughly learn the design, the operations to be performed, the facilities to be used, the data to be recorded, the cleanliness practices to be observed — and in most cases, prepare themselves to be able to do practically all of the operations, because subsequently they had to train selected operators to perform critical operations to very high quality standards under rigidly controlled manufacturing conditions. As shop supervisors and employees were assigned to the manufacture of repeaters, they were thoroughly indoctrinated in the design intent and the new philosophy of manufacture.

Standard ability and adaptability tests were used in a large number of cases to assist in proper selection and placement of technicians. Tests for finger and hand dexterity; sustained attention; eyes, including perception and observation; and reaction time of the right foot after a visual stimulus. (The latter test was relatively important for induction brazing operations.) Other requisite considerations were a high degree of dependability and integrity, involving intellectual honesty and conscientious convictions; capability of performing tedious, frustrating, and exasperating operations against ultra-high quality standards, verifying their own work; perseverance and capability to easily adapt to changes in assignment and occupation or the introduction of design changes. We considered whether or not they would stand up under "fishbowl" operations, wherein they would receive a considerable amount of observation from high levels of Western Electric Company and Bell System management and other visitors. Also, could they duplicate high quality frequently after qualifying for a particular operation?

During the period of repeater manufacture, the number of employees rose from less than 50 in January, 1954, to a maximum of 304 by February, 1955, after which there was a gradual reduction to a level of about 265 employees for six months and then a gradual falling off as we were completing the last of the project. In the period from May to December, 1954, between 30 and 45 employees were constantly in training prior to being placed on productive work. During 1955 this decreased to practically no employees in training during the midpart of the year and thereafter training was required merely to compensate for a small labor turnover and employee reassignment. It is significant that labor turnover was very low and attendance was exceptionally good during the life of the Hillside operations.

Personnel Training

The original plan, which was generally followed, was to prove in the tools for each phase of the job, followed by an intensive program of train-

ing. Indoctrination of laboratory technicians could be considered as "vestibule training" in that they were acclimated to the area and conditions, given oral instruction in the work, then given practice materials and demonstrations and, when qualified, were started on making project material. To do this, extra supervisors were required at the beginning of the job. A supervisor trained a few employees, qualified some of them, and began work on the project. Another supervisor was then required to train additional employees who, as they became qualified, were transferred to the supervisor responsible for making project apparatus. Additional testing of the employees, instruction and reinstruction and, in some cases, retraining were required. In practically all cases, we were able to fit an employee selected for work at Hillside into some particular group of operations. The extra emphasis on selection and training created a well-balanced team that later resulted in considerable flexibility. During all of this training our supervisors worked closely with engineers and inspectors who understood the design intent and the degree of perfection required.

At the beginning, each technician was trained for only one operation of a particular job, such as (1) winding Type X capacitors or (2) impregnating all paper capacitors or (3) winding Type Y transformers and so became an expert on this one operation. Later, the tours of duty for many technicians were broadened to cover several operations.

Communications

To keep employees informed, we occasionally assembled the entire group, presenting informative talks on current production plans and our future business prospects. Motion pictures were shown of the cable laying ships and the operations of cable splicing and cable laying. A display board, showing all of the repeater components, was mounted on the wall of the cafeteria. This informed the operators just where the parts were used in apparatus; also, just where their products went into the wired repeater unit, and how all electrical apparatus was enclosed against sea pressure in the final repeater. In small groups, all of the employees at Hillside were given a short guided tour of the plant to see the facilities and hear a description of the operations being performed in each area. These communications were extended to everyone at the Hillside Plant, including those who did not work directly on the product. It was our conviction that the maintenance men, boiler operators, oilers, station wagon chauffeur, janitors, and clerical workers in the office were all interested and could do a better job if kept informed of the needs and progress of the project.

Scheduling

Capacity was provided at the Hillside Shop to manufacture a maximum of 14 repeaters in a calendar month. This envisioned 6-day operation with some second and third shift operations; due allowance was made for holidays and vacations, so that the annual rate would be approximately 160 enclosures per year. (An enclosure is either a repeater or an equalizer.)

Some of the facilities and raw materials were ordered late in 1953. This ordering expanded early in 1954 and continued through 1955 to include parts to be made by outside suppliers and the parts and apparatus to be made at Hillside. Apparatus designs were not all available at the beginning of the job, and the ultimate quantities required were also subject to sharp change as the project shaped up, thus further complicating the scheduling problem.

Because of the time and economic factors involved, coupled with the developmental nature of the product and processes, one of the most difficult and continuing problems was the balancing of production to meet schedules. For this task, we devised "tree charts" for the apparatus codes and time intervals in each type of repeater or equalizer for each project. Each chart was established from estimates of the time required to accomplish the specified operations and the percentage of good product each major group of operations was expected to produce.

RAW MATERIALS

Many of the specifications were written around the specific needs of the job and embodied requirements that were considerably more stringent than those imposed on similar materials for commercial use. As a result, it was necessary for many suppliers to refine their processes, and, in some cases, to produce the material on a laboratory basis.

One example is the container, or repeater enclosure, which consists, in part, of a seamless copper tube approximately $1\frac{3}{4}$ inches in diameter having a $\frac{1}{32}$-inch wall and approximately 8 feet long. This material was purchased in standard lengths of 10 feet. The basic material was required to be phosphorous deoxidized copper of 99.80 per cent purity. The tubing, as delivered, had to be smooth, bright, and free from dirt, grease, oxides (or other inclusions including copper chips), scale, voids, laps, and slivers. Dents, pits, scratches, and other mechanical defects could not be greater than 0.003 inch in depth. The tubing had to be concentric within 0.002 inch and the curvature in a 10-foot length not exceed $\frac{1}{2}$ inch to facilitate assembly over the steel rings.

Only one supplier was willing to accept orders for the tubes, and only on the basis of meeting the mechanical requirements on the outside surface. To establish a source of supply, it was necessary to accept the supplier's proposal on the basis that some of the tubes produced could be expected to meet requirements on the inside as well as the outside surface. Inspection of the inside surface was performed with a 10-foot Borescope.

The supplier then set aside, overhauled, and cleaned a complete group of drawing facilities for this project. In addition, a number of refinements were made in lubrication and systematic maintenance of tools. After all refinements were made and precautions taken, however, the yield of good tubes in the first 400 produced was less than 1.0 per cent. Consultations with Western and Bell Laboratories' engineers, and with the supplier's cooperation, raised the yield to approximately 50 per cent.

Procurement of satisfactory mica laminations for capacitors introduced an unusual problem. The best grade of mica available in the world market was purchased which the supplier, under special plant conditions, split and processed into laminations. Despite care in selection and processing, only 50 per cent of the 250,000 laminations purchased met the extremely rigid requirements for microscopic inclusions and delaminations, and less than 8 per cent survived the capacitor manufacturing processes.

A large number of the parts, and the most complex, are made from methyl-methacrylate (Plexiglass). At the time manufacture began, there was little, if any, experience or information available on machining this material to the required close tolerances and surface finish. Consequently, considerable pioneering effort was expended in this field before satisfactory results were obtained.

The methacrylate parts cover a wide range of size and complexity — from $1\frac{1}{2}$-inch diameter by $4\frac{7}{8}$-inch long tubular housing to tiny spools $\frac{1}{8}$-inch diameter and $\frac{1}{16}$-inch long. Most of the parts are cylindrical in shape with some semicylindrical sections that must mate with other sections to form complete cylinders. Others have thin fins, walls, flanges and projections. Five representative parts are shown in Fig. 2.

Methyl-methacrylate has a tendency to chip if tools are not kept sharp and care is not used in entry or exit of the tool in the work, particularly in milling. In some cases, it is necessary, with end-milling, to work the cutter around the periphery of the area for a slight depth so that subsequent cuts will not break out at an unsupported area. Normally, with a sharp cutter and a 0.010-inch finish cut, and a slow feed, chipping will not result. High-speed steel tools with zero rake were used for turning

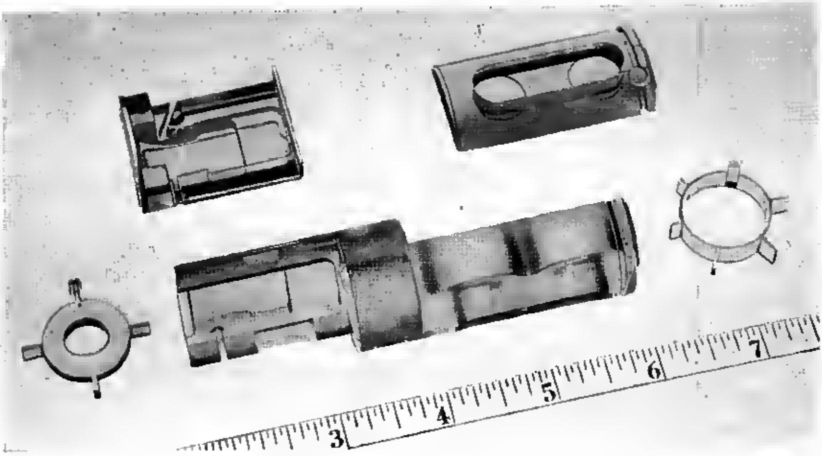


Fig. 2 — Methyl methacrylate parts.

and boring operations. Standard high-speed milling cutters and end mills were used for milling except for the cutting edges, which are honed to a fine finish. A clearance angle of 7 degrees for milling and 10 degrees to 15 degrees for lathe work was found most satisfactory. In lathe work, the general rule was light feeds (0.003 inch–0.005 inch) and small depth of cut. However, the depth of cut could be safely varied over a wide range depending upon many factors, such as type of part, quality of finish, machine and tool rigidity, effective application of coolant, and tooling to support and clamp the part. In one operation of boring a $1\frac{3}{16}$-inch diameter by $4\frac{1}{8}$-inch deep blind hole within ± 0.002 inch, the boring terminates in simultaneously facing the bottom of the hole square with its axis. A cut $\frac{19}{32}$-inch deep with a light feed was taken with a specially designed boring tool with the coolant being fed through the shank to the cutting edge. All completely machined parts were annealed for 12 hours at 175° F.

HIGHLIGHTS IN ASSEMBLY AND BRAZING

Repeater units are encased in hardened steel rings which previously had been tested at 10,000 pounds per square inch hydraulic pressure. This pressure is approximately 50 per cent higher than the greatest pressure expected at ocean bottom. The steel rings were encased in a copper sheath and closed at each end with a glass-to-Kovar seal, with the central conductor coming through the glass to the outside. The copper sheath was then shrunk to the steel rings and glass seals using 6000 pounds per

square inch hydraulic pressure, and the glass seal was then high-frequency brazed to the copper sheath.

To keep the ocean bottom pressure off the glass seals and also to terminate the cable insulation, a rubber seal is brazed in to the copper container tube adjacent to each glass seal. This rubber seal consists of rubber bonded to brass, which has been brazed to the copper portion of the seal. The rubber terminates iu polyethyleue through five steps of compounds containing successively less rubber and more polyethyleue. The polyethylene can be readily bonded by moldiug to the polyethyleue insulation of the cable. The central couductor passes through a central brass tube in the rubber seal, which is also bonded to the rubber.

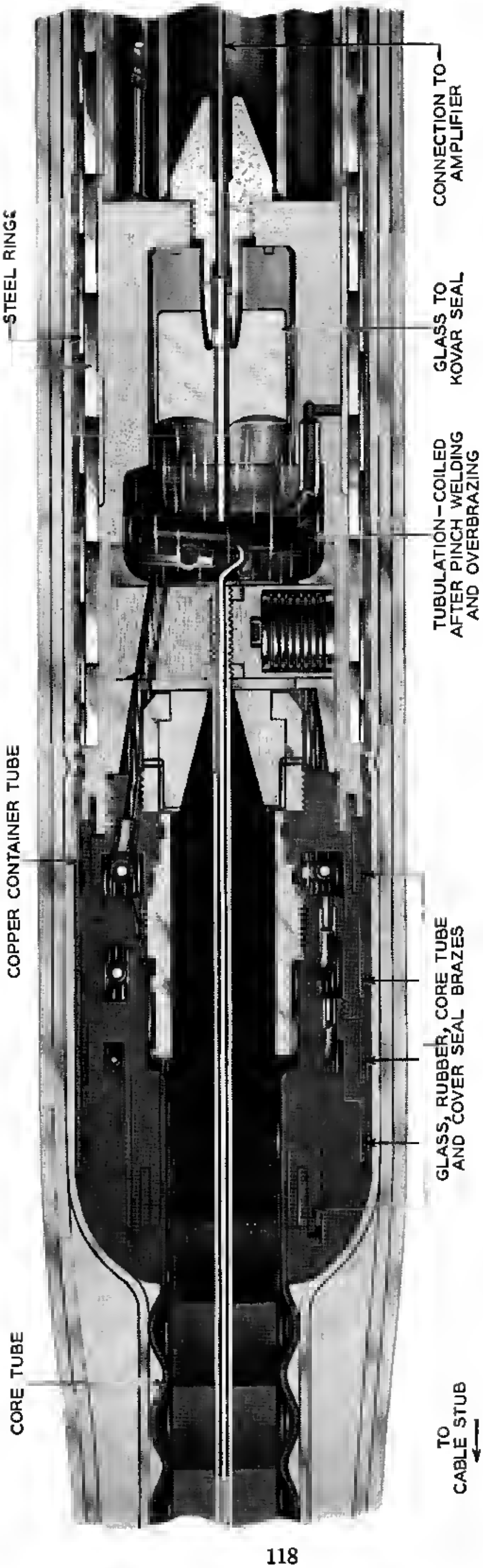
To protect the rubber seals from the deleterious effects of salt water immersion for long periods of time, a copper core tube is brazed over each rubber seal. The core tube is arranged to equalize the pressure inside and out when submerged at ocean bottom pressure. This is accomplished with a bulge of neoprene filled with polyisobutylene, on the far end of the core tube, which transmits the pressure to the inside of the core tube seal.

To make doubly sure that no salt water reaches the rubber seal, a copper cover is brazed into the container outside the core tube connector on each end. This cover is also brazed to the core tube connector. The interstice between each of the above four seals is filled with polyisobutyleue, which is viscous and inert and has very good insulating qualities.

Each end of the repeater closure (Fig. 3) contains five successive brazed joints. Any one of these ten brazes, if not perfect, could cause the loss of the repeater closure and jeopardize the entire repeater. All of these brazes were made with the repeater in a vertical position to insure an even distribution of the brazing alloy fillet around the joint.

An upending device was provided at the pit brazing location to raise the repeater on its carrier to a vertical position with either end up and move it into position for brazing. The repeaters were brought into the brazing area on an overhead monorail and an electric hoist. The shorter repeater assemblies, before core tube and cable stub assembly, were upended by hand and brazed from a raised platform.

It was necessary to make all of these brazes by high-frequency induction heating, since the heat must be intense, contained within a very narrow band, evenly distributed, and the area protected from oxidation by a somewhat reducing atmosphere. The heat must be very intense since the time interval for the shortest braze was 10 secouds maximum and the longest was 30 seconds. A large part of the heat was dissipated



F. 3 — Repeater seals.

by being conducted at a high rate from the copper parts to the water in the cooling jackets used to contain the heat in a very narrow band.

Circulating cooling water within a jacket prevented heat from being conducted down the copper container tube to the preceding seals or to the repeater unit. This water-cooled jacket was positioned only $\frac{3}{8}$ inch below the inductor, and the water was in iutimate coutact with the container tube, which is sealed off at both ends with rubber "O" rings. In addition, for the glass seal braze, the glass inside the seal cavity was kept covered with water during the heat cycle. The water was fed in and siphoned out to a constant level which was kept under observation by the operator and the inspector to make sure that the glass was covered at all times. The rubber seal was also water jacketed on the inside of the seal to prevent deleterious effects of the heat on the rubber insulation around the central conductor. The inner cover braze was quenched before the 10-second maximum interval had expired to insure that the heat did not penetrate to the polyisobutylene at a sufficient rate to deteriorate it or the rubber inside.

Distribution of the heat around the container tube at the braze area was controlled by locating the work in the inductor so that the color came up essentially evenly all the way around and at the proper level to bring a fillet up to the top of the braze joint within the allowable time limit. The time limit was determined by experiment so that none of the previously assembled parts were damaged by the heat. This determination of the proper heat pattern and the prevention of overheating required the development of considerable skill on the part of the operator. The variables encountered made it essential to rely on an operator to control the heat rather than to utilize the timer with which the induction heating equipment is normally controlled.

The area to be heated for brazing was protected from oxidation by enclosing it in a separable transparent plastic box and flooding the interior with a gas consisting of 15 per cent hydrogen and 85 per cent nitrogen. This atmosphere is somewhat reducing and not explosive. The brazing surfaces of the parts were chemically cleaned immediately before assembly and extreme care was exercised to keep them clean until brazed.

The container tube was shrunk to the respective glass, rubber, core tube, and cover seals using hydraulic pressure so that the surfaces to be brazed and the brazing alloy were in intimate contact within the brazing area. If the parts were clean and kept from oxidizing by the protective atmosphere, the alloy would flow upward by capillary action and form a fillet around the top of the seal, impervious to any leak.

The braze in each case was then leak tested with a helium mass-spec-

trometer type leak detector. A gas pressure of helium at least 25 per cent greater than the maximum pressure to be encountered at ocean bottom was used. In addition, a radioisotope was used to test the effectiveness of the final tubulation pinch welds and overbrazes which were kept open for the leak tests under high pressure helium. These tests were made with water pressure about 25 per cent greater than the maximum ocean bottom pressure.

The completed repeater was inserted in a chamber 80 feet long; the chamber was then filled witb water and the pressure raised to 7,500 pounds per square inch and held at that pressure for at least 15 hours. At the end of this period the closure had to show no sign of crushing or leaking.

Tbe repeater unit sealed in the closure must be extremely dry to function properly. Any water vapor which might remain after the closure is sealed, or enter during the estimated 20-year minimum life, must be scavenged. A sealed desiccator with a thin diaphragm was, therefore, assembled into the repeater unit sections. After completely drying and sealing the repeater unit except for one tubulation, the diaphragm of the desiccator was ruptured by dry nitrogen pressure and with the enclosure filled with dry nitrogen the final tubulation was immediately sealed off. To insure that the diaphragm was actually broken, a microphone was strapped to the outside of the repeater over the location of the desiccator and a second microphone arranged at the end of the closure to pick up background noises. A pen recorder was used to record the sound from the two microphones and also the change in nitrogen pressure. Three simultaneous pips on the chart gave definite indication that the diaphragm had ruptured and that the desiccant had been exposed to the internal atmosphere of the repeater.

QUARTZ CRYSTAL UNITS MANUFACTURED AT KEARNY

The primary purpose of the crystal unit is to provide the means of identifying and measuring the gain of each repeater in the cable. This basic crystal design is in common usage. The exacting specifications for this application, however, imposed many problems and deviations from normal crystal manufacturing processes.

Raw Quartz was specially selected for this crystal unit. The manufacturing process of reducing the quartz to the final plate followed the recognized methods through the roughing operations. Due to the rigid end requirements, the finishing operations were performed under laboratory conditions. Angular tolerances were one-third of normal limits. No evidence of surface scratches, chipped edges or other surface imper-

fections visible under 30X magnification were permitted. This resulted in a process shrinkage five times that experienced in normal crystal plate manufacture.

In this use, the crystal units were required to meet performance tests at currents as low as one-thousandth of a microampere — far below tbe current values usually encountered. Improved soldering tecbniques had to be developed for soldering the gold plated phosphor bronze and nickel wires used, because it was found that the electrical performance of the units was directly related to the quality of soldered connections.

Although one-seventh of Western's production of quartz crystal units are in glass enclosures, the applicable techniques in glass working required a complete revision. Glass components such as the stem and bulb purchased from established sources were found to be far below the standard required for this crystal unit. For example, the supplier of the glass tubing used in the manufacture of stems was required to meet raw material specifications that embodied coefficient of thermal expansion, softening point of glass, density, refractive index, and volume resistivity. The glass stems made from this tubing by regular manufacturers were found unacceptable and the processes used by these sources could not be readily adapted to meet the desired specifications. The glass stems contained four lead wires made from 30-mil Grade "A" nickel wire butt welded to 16-mil light borated Dumet wire. To assure the quality of the metal to glass seal, each wire was inspected under 30X magnification for tool marks and other surface imperfections. The finished stem assemblies were inspected under 30X magnification for dimensions, workmanship, cleanliness and minute glass imperfections, then individually stored in a sealed plastic envelope.

The glass bulb in this crystal unit is known as the T921 design commonly used in the electron tube industry. Tbe higb quality required, however, made 100 per cent inspection necessary. Examination under 30X magnification resulted in rejected bulbs for presence of scratches, open hubbles, chips and stones. Physical limits for inside and outside diameters as well as wall thickness were causes for additional rejects. Only one per cent of the commercial bulhs were found acceptable, and these were also stored in a sealed plastic envelope.

The final major assembly operation consisted of sealing the glass bulb to the stem which had had the crystal sub-assembly welded to the nickel wires. The techniques for "sealing in" used in quartz crystal or electron tube manufacture were unsuited. Two important factors in this crystal unit, which required the development of new processes, were tbe proximity of soft soldered connections to the sealing fires and the demands

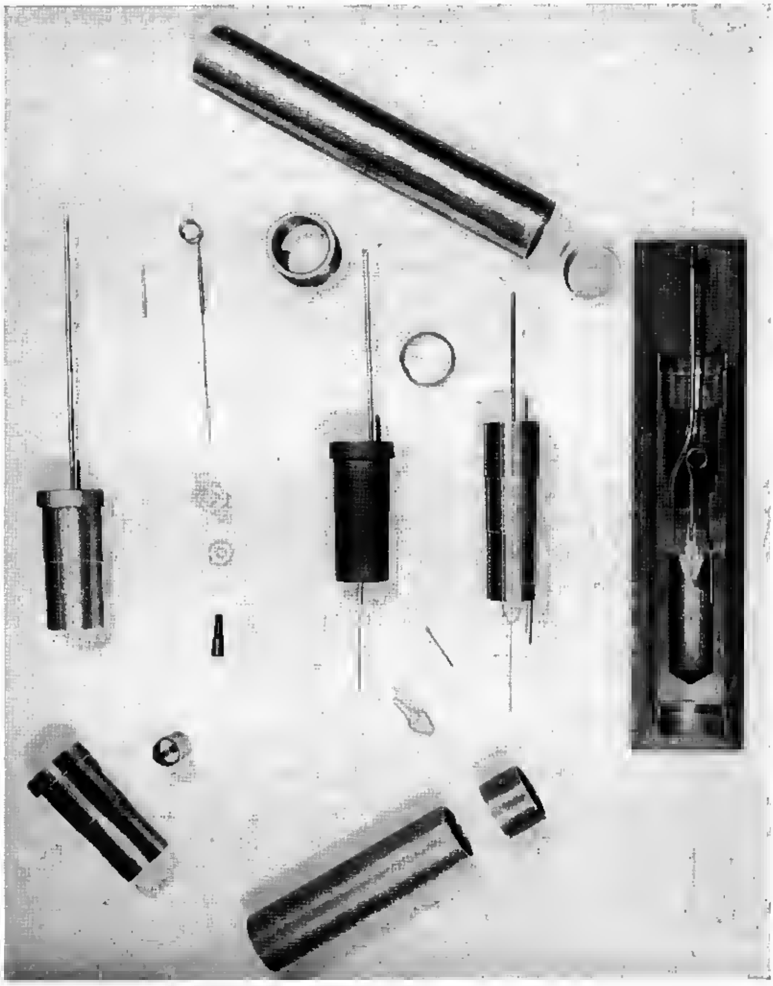


Fig. 4 — Glass to Kovar seal.

that the glass seal contain a minimum of residual tensile stress. These two problems were resolved collectively by performing the sealing operation on a single spindle glass sealing machine. Accurate positioning of the glassware and sealing fires, together with precise timing and temperature controls, achieved the desired results.

Evaluation of residual stresses were made by inspections using a polarimeter and by a thermal shock test. The maximum safe stress was established at 1.74 KG/mm^2. Tbe thermal shock test required successive immersion of the unit in boiling water and ice water. The electrical characteristics of these units exceeded all otbers made previously by Western Eleetrie. The ratio of reactance to effective resistanee ("Q") was greater than 175,000 — twice that ever previously produced and 17 times that required in the average filtêr crystal.

Stability for frequency and resistance was assured by a 28-day aging test. During this period, precise daily resonant frequency and resistance measurements were recorded against temperature within 0.1° C. The maximum permissible change was 0.0005 per cent in frequency and +5 per eent to −10 per cent in resistance.

GLASS SEALS MANUFACTURED AT ALLENTOWN

The glass seal used to close each end of the container for the repeaters and equalizers is manufactured at the Allentown Works of the Western Electric Company.

The unit is essentially a glass bead-type seal. It insulates the central conductor of the repeater from the container and serves as a final vapor barrier between the cable and the interior of the repeater. As such, it backs up several other rubber and plastic barriers as shown in Fig. 3.

Fig. 4 shows the various components, subassemblies, and a cross-section of the unit. The unit consists of the basic seal brazed in the Kovar outer shell, to which is brazed a copper extension provided with two brazing-ring grooves. One of these grooves is used in brazing the seal, along with support members, into a length of container tubing in the same manner as the seal is ultimately brazed into the repeater. Packaging of the seal in this manner was necessary to pressure test the seal. Under test, in a specially eonstructed chamber 10,000 psi of helium gas pressure was applied to the external areas of the packaged glass seal and a mass spectrometer type leak detector was connected through the tubulation to the internal cavity of the packaged unit. In this manner, the interface of the glass to metal seal, the brazed joints, and the porosity of the metal were checked for leakage. The unit is left in this package for delivery to provide protection during shipment. Before the seal could be used,

it was machined from the package by cutting the copper extension to length, leaving the second groove for use in brazing the seal to the repeater and removing the container tubing and the support members.

The basic seal consists of the cup, central conductor and glass. The cup (smaller cylindrical item in the upper lefthand corner of Fig. 4) was machined from Kovar rod. The wall of the cup is tapered from a thickness of 0.025 inch at the base to 0.002 inch at the lip. The last 0.006 inch of the lip is further tapered from this 0.002 inch to a razor edge. The internal surface is better than a 63-micro-inch turned finish and was also liquid honed to give it a uniform matte finish. The central conductor (slim piece in the upper right-hand corner of Fig. 4) was also machined from Kovar rod. Both the cup and central conductor were further processed by pickling, hypersonically cleaning in deionized water, and decarburizing. The glass, a borosilicate type of optical quality, was cut from heavy walled tubing. The glass tubing was hand polished, lapped and etched to remove surface scratches, and to arrive at the specified weight. It was also fire polished and hypersonically cleaned to remove all traces of surface imperfections and to assure maximum cleanliness.

In order to make the basic glass seal, the metal parts had to be oxidized under precisely controlled conditions. For the oxidizing operation, a suitable fixture was loaded with brazed shell-cup assemblies, central conductor assemblies, and a Kovar disc, which had been prepared in precisely the same manner as the cups and central conductors. The disc was carefully weighed before and after oxidizing and the increase in weight divided by the area involved yields the weight gain due to oxidation for each run. Limits of 1.5 to 2.5 milligrams per square inch of oxide were set. This operation was performed by placing the loaded, sealed retort, through which passed a metered flow of dried air, into a furnace for a specified time-temperature cycle.

In the glassing operation the oxidized shell assembly, the carbon mold and the central conductor were placed in a fixture and held in the proper relationship. The carbon mold served to support the glass, while it was being melted, in that section between the cup and central conductor where the glass was normally unsupported. The prepared cut glass tubing was loaded into the Kovar cup and the fixture was sealed into the retort. During the glassing cycle, a constant flow of nitrogen passed through the retort to provide an atmosphere which minimized any reduction or further oxidation of the already carefully oxidized parts. After the proper purging period, the retort was placed in the furnace. In the furnace, the glass melted and formed a bond with the oxidized Kovar of the cup and

central conductor to form the seal. After the specified temperature-time cycle, the retort was removed from the furnace, allowed to partially cool and then placed into an annealing oven.

Vertical furnaces and retorts were used for brazing, decarburizing, oxidizing and glassing. By varying the type of gases flowing into the retorts, atmospheres which are reducing, oxidizing, or neutral were obtained. To provide maximum uniformity of process, separate retorts and holding fixtures were provided for operations involving hydrogen and for air-nitrogen operations, so that a retort or a fixture used for hydrogen treatments was never used for oxidizing or glassing.

PILOT AND REGULAR PRODUCTION

We called our first efforts *Practice Parts and Training;* the next we called Pilot Production. Next, certain items identified as *Trial Laying Repeaters and Oscillators* were manufactured for use in "proving in" the ship laying gear. To prove in manufacturing facilities, a few unequipped housings were made without the usual electrical components normally in a repeater. Similarly, each of the apparatus components and parts required exploratory and pilot effort before regular production could be undertaken.

As might be expected, the manufacturing yield of components meeting all requirements was very low during the early stages of the undertaking. However, substantial improvement was brought about as experience was gained. Comments on some of the production problems, highlights, and yield results, follow.

Paper Capacitors were manufactured only after painstaking qualifying trials and tests had been performed on each individual roll of paper. Cycling and life testing, procurement of acceptable ceramic parts and gold-plated tape and cans, selection and matching of rolls of paper for winding characteristics, and similar problems, all had to be completely resolved to a point of refinement previously unattempted for telephone apparatus.

Composite percentage yield for all operations on paper capacitors is shown in Fig. 5. Yield is shown as the ratio of finished units of acceptable quality to the number of units started in manufacture.

Mica Capacitors were made from only the most meticulously selected laminations, as mentioned earlier. Even the best mica is particularly susceptible to damage in processing. In spite of experience and knowledge of this, the multiple handling of the laminations contributed an unusually high material shrinkage as each separate lamination needed to be cleaned, then handled individually many times through the proc-

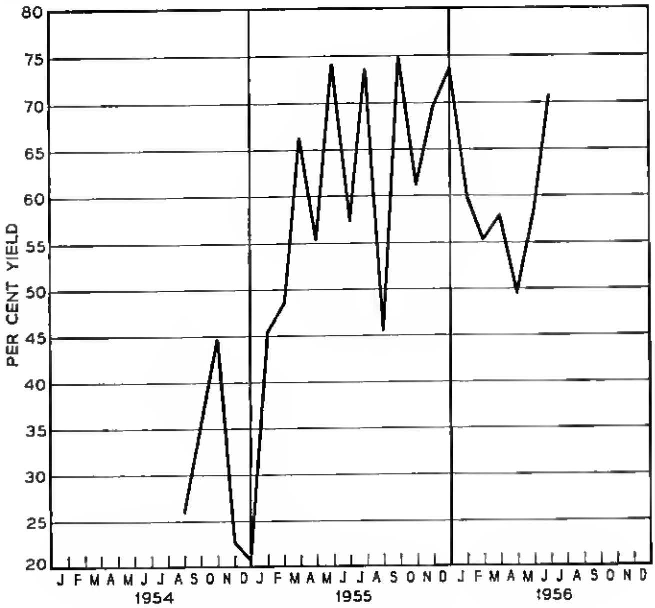


Fig. 5 — Paper capacitor yield.

esses. The art of silk screening was applied to deposit silver paste in a specific area or areas on each side of a lamination. A sharply defined rectangular area was required so that when superimposed one over another the desired capacitance would be obtained. Cementing of mica laminations onto machined methacrylate forms presented some additional prohlems through the bowing of the mica laminations as the cement cured. Ohtaining screens that would give the proper length and width dimensions for the coated area, was another prohlem. A silk screen woven of strands of silk obviously limits, hy the diameter of the threads, the extent to which the dimensions of an opening may be increased or decreased. Beryllium copper U-shaped terminals were used to clamp the layers of mica together into a stack. Control of the pressure used in crimping these terminals was found to be very eritical in view of the exceptionally tight limits on capacitance and stahility. Fig. 6 shows the composite yield at various times for all mica capacitors.

Resistors. There were three designs of ceramic resistors, which were resistance-wire wound on ceramic spools. These were intended to he assembled into the hole inside the core tube on which the paper capacitors were wound. Special winding machines equipped with hinocular

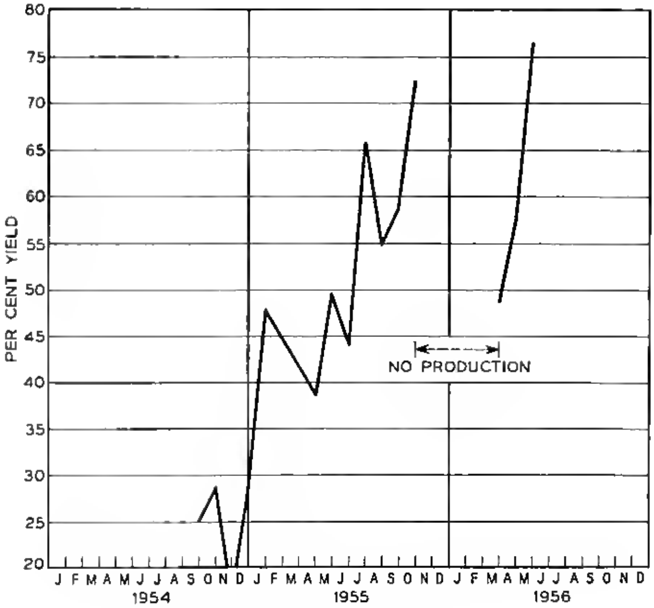


Fig. 6 — Mica capacitor yield.

attachments were necessary to wind these resistors. Other resistors were hand wound on methyl-methacrylate forms, or on the outside of the ceramic containers, for certain types of paper capacitors. Rough adjustments were required of the lengths of resistance wire prior to winding, and close adjustments to resistance values were made after the windings were completed and before leads were attached to resistors. Again it was necessary to provide periodic samples that could be placed on life test by the Laboratories to ascertain that the manufacturing processes were under control. These samples, in all possible cases, were taken from product that would normally be rejected because of some minor defect, but which would not in any way detract from the validity of the life tests. The making of hard solder splices between nichrome resistance wire and gold-plated copper leads, and keeping ceramic parts from coming in contact with metal surfaces and thereby being contaminated because of the ceramic's abrasive characteristics, were two major problems on resistors. Fig. 7 indicates resistor yields.

Inductors comprised 20 different designs, most of which were air core, but there were some for which it was necessary to cement permalloy dust cores into pockets of the methacrylate form, and thereafter using

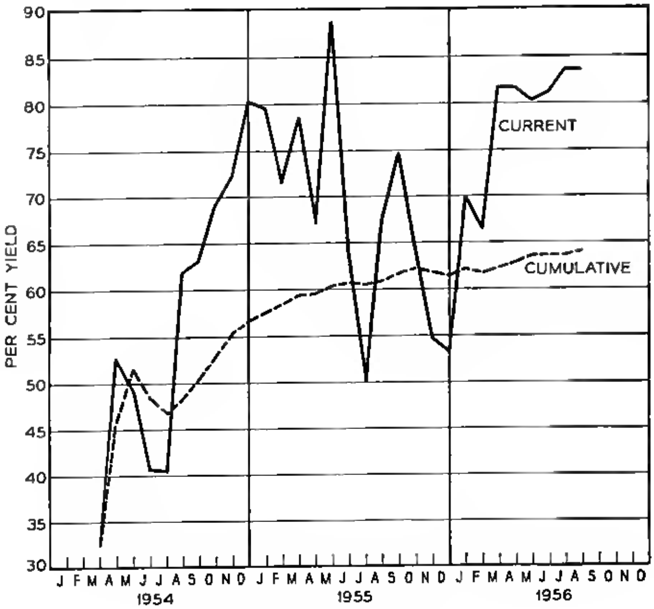


Fig. 7 — Resistor yield.

wire on a shuttle, wind by hand the turns required to produce an inductor. These varied from a very small inductor, smaller in diameter than a pencil, to a fairly large "figure eight" inductor with turns having a major diameter of about $1\frac{1}{4}$ inches. Each layer of a winding was inspected with a microscope to insure that the wire had not been twisted or kinked, or that the insulation was damaged or uneven. Some of the shuttles became fairly long so that they could hold the amount of wire required to make a continuous winding. The operator's handling of this shuttle, as she moved it down around the openings in the methacrylate part, or placed it on a bench to proceed with the interleaving tape, demanded considerable dexterity and concentration to insure that the shuttle was not turned over — which in effect would put a twist in the wire. Although best known means were used to sort cores for their magnetic properties prior to the time a winding was made, the limits on the inductors themselves were so close that subsequently a large number of windings were lost. The best cores that could be selected, plus the best winding practice, could not produce 100 per cent of the inductors within the required limits. Crazing of the insulation on the wire; cementing together of two methacrylate parts or of permalloy cores into pockets of

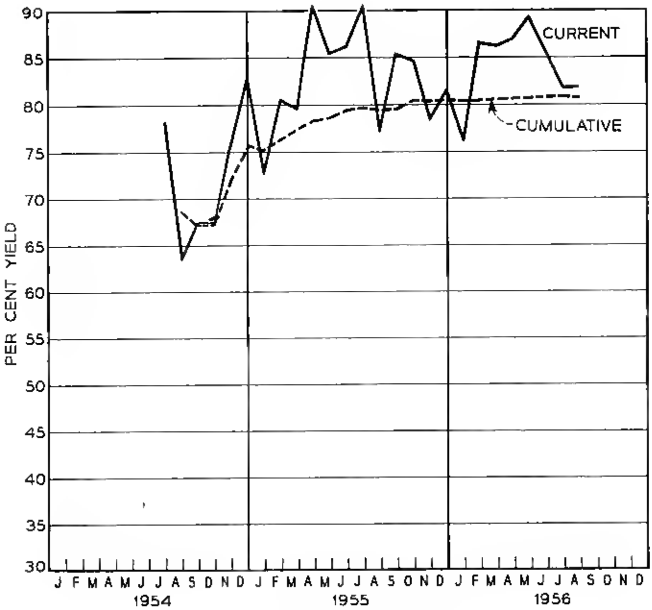


Fig. 8 — Inductor yield.

methacrylate parts, and handling those inductors having long delicate leads, were the most troublesome items on this apparatus. Fig. 8 shows manufacturing yield for inductors.

Networks combined several codes of component apparatus, such as a mica and a paper capacitor, resistor and an inductor. Six networks were used in each repeater unit consisting of two interstage networks, an input, an output, and two beta networks. They demanded a most delicate wiring job in that stranded gold-plated copper wires had to be joined in a small pocket in methyl methacrylate, where a minimum amount of heat can be applied; otherwise the methacrylate is affected. After soldering, a minimum amount of movement of the stranded wire was permitted, inasmuch as the soldered gold-plated copper wire becomes quite brittle.

Repeater Units, are wired assemblies consisting of seventeen sections in which there are six networks, three electron tubes, one gas tube, one crystal, three high voltage capacitors, one dessicator and two terminal sections. The successive build-up of these materials left little chance to make a repair because a splice in a lead was not permissible. It is during this assembly stage that a repeater received its individual identity be-

cause of the frequency of the particular crystal assemhled into the unit. A manufacturing yield of 100 per cent was achieved in the assemhly and wiring of repeater units.

It was necessary to calihrate the test equipment for this joh very closely. Bell Telephone Lahoratories and Western Electric worked at length to calihrate the testing details and the test sets for individual networks. Adjustments in components apparatus to hring the network to the fine tolerances required were accomplished hy minute scraping of the silvered mica on a mica capacitor or removing turns from wire-wound inductors. The cementing of methacrylate parts, which was a trouhlesome item on mica capacitors and inductors, also had to he contended with on networks.

PACKING AND SHIPPING COORDINATION

Repeaters were packed in Western Electric specially designed 34-foot long aluminum containers, weighing 1,000 pounds. Forty of these containers were made hy an outside firm. Fig. 9 shows two containers tied down in a truck trailer. The repeaters were nested in a pocket of polyethylene hags containing shaped ruhherized hair sections in order to cushion the repeaters during their suhsequent handling and transportation. The instrumentation required with each case was tested, properly set, and inspected prior to its use on each outgoing case. The instruments were a shock recorder to register shocks in three planes, and a thermometer to register the minimum and maximum temperatures to which the repeater had heen exposed. Arrangements were made with a commercial trucking company to provide three specially equipped truck trailers, which could he cooled hy dry ice during hot weather and warmed hy hurning hottled gas during cold weather so as to control temperature within the 20-degree F. to 120-degree F. called for in the repcater specification.

Appointment of a shipping coordinator supervisor added tremendously to the smooth functioning of services and provided the continuing vigilance required to protect repeaters and deliver them to the right place at the right time. His responsihility was to coordinate all the shipping information and arrangements from the time the item was ready for packing at the Hillside plant, through all trucking arrangements to the armoring factory, to the airport, to England, and to follow, with statistical data and reports, each enclosure until we were ahle to record the date on which the repeater was laid or stored in a depot.

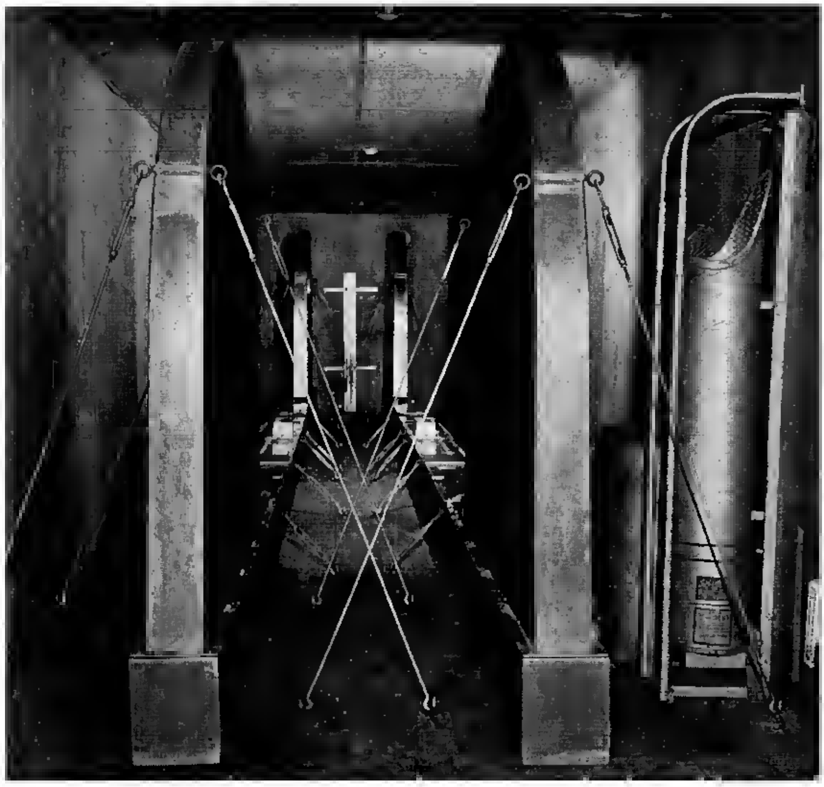


Fig. 9 — Shipping containers.

INSPECTION PLAN AND PROCEDURES

General

It is axiomatic that quality is not obtained by inspection but must be built into the product. However, the Inspection Organization does have the responsibility of certifying that the desired quality exists. Our evaluation indicated that the ordinary inspection "screening" would be inadequate to insure the high degree of integrity demanded and that additional safeguards would have to be provided. These controls were achieved, in a practical way, by:

(1) Selective placement, intensive training and subsequent qualification testing of all personnel.

(2) Inspection during manufacturing operations in addition to in-

spection of product after completion, and regulating inspection so that critical characteristics received repetitive examination during the process of manufacture and assembly.

(3) A maintenance program for inspection and testing facilities which provided checks at considerably shorter intervals than is considered normal.

(4) Inspection and operating records and reports that point out areas for corrective measures.

(5) Records of quality accuracy for all inspection personnel as an aid in maintaining the high quality level.

(6) Verification of all data covering process and final inspection as a certification of tbe accuracy of these data and that the apparatus satisfactorily meets all requirements.

Selection and Training of Inspection Personnel

The quality of a product naturally depends upon the skills, attitude, and integrity of the personnel making and inspecting it. It was realized that in order to develop the high degree of efficiency in the inspection organization necessary to insure the integrity of the product, personnel of very high caliber would be required. Tbese employees would have to be (1) experienced in similar or comparable work, (2) they would have to be precise, accurate and, above all, dependahle, (3) in order to reduce the possihility of contamination and damage they would have to be neat and careful, and (4) they would require the ability to work in harmony with other employees, often as a member of a "team," in an environment where their work would be under constant scrutiny.

Most of the inspection employees selected to work at Hillside were transferred from the Kearny Plant and had an average Western Electric service of twelve years. They were hand-picked for the attributes outlined above, and the "screening" was performed hy supervision through personal interviews supplemented hy occupational tests given by tbe personnel department. These tests, which are in general use, are designed to evaluate background and pbysical characteristics, and they were given regardless of whether the employee had or had not previously taken them.

The following group of tests is an example of those given inspectors and testers of apparatus components:

(1) Electrical — ac-dc theory and application.

(2) Ortho-Rater — Eye test for phoria, acuity, depth, and color.

(3) Finger Dexterity — Ahility and ease of handling small parts.

(4) Special — Legibility of handwriting, ability to transcribe data and to use algebraic formulae in data computations.

Inspection Plan

The general plan of visual and mechanical inspection consisted of:

(1) Inspection of every operation performed — and in many cases partial operations — during the course of manufacture. This is of particular importance where the quality characteristics are hidden or inaccessible after completion of the operation.

(2) Repeated inspection at subsequent points for omissions, damage and contamination.

(3) Rejection of product at any point where there was failure to obtain inspection or where the results of such inspection had not been recorded.

Most of the visual inspection was performed at the operators' positions to reduce, to a minimum, the amount of handling that could result in damage and contamination.

Visual inspection covered three general categories:

(1) Inspection of work after some or all operations had been completed, such as the machining of parts.

(2) Inspection at those points where successive operations would cover up the work already performed. An example of this is the hand winding of toroidal inductors where each layer of wire was examined under a microscope for such defects as twists, cracks, and crazes in enamel insulation, spacing and overlapping of turns, and contamination before the operator was allowed to proceed with another layer. While being inspected, the work remained in the holding fixture, which was hinged in such a manner as to permit inspection of both top and bottom of the coil. Inductors received an average of 13 and a maximum of 26 visual inspections during winding.

(3) Continuous "over-the-shoulder" inspection, where strict adherence to a process was required or where it was impossible to determine, by subsequent inspection, whether or not specific operations had been performed. In these cases, the inspector checked the setup and facilities, observed to see that the manufacturing layouts were being followed, that the operations were being performed satisfactorily, and that specifications were being met.

ELECTRICAL TESTING

The electrical testing, in itself, was not unusual for carrier apparatus and runs the gamut from dc resistance through capacitance, inductance,

and effective resistance, to transmission characteristics in the frequency band 20–174 kc. What was unusual were the extremely narrow limits imposed and the number and variety of tests involved as compared to those usually specified for commercial counterparts.

The following two examples will serve to illustrate the extreme measures taken to prove the integrity of the product:

(A) One type of Resistor was wound with No. 46 mandrelated nichrome wire to a value of 100,000 ohms plus or minus 0.3 per cent. This resistor received six checks for dc resistance, five for instantaneous stability of resistance and two for distributed capacitance, at various steps in the process which included six days' temperature cycling for mechanical stabilization. This resistor was considered satisfactory, after final analysis of the test results, if: (a) The difference in any two of the six resistance readings did not exceed 0.25 per cent. (b) The change in resistance during cycling was not greater than 0.02 per cent. (c) The "instantaneous stability" (maximum change during 30 seconds) did not vary more than 0.01 per cent. In addition, it was required that the distributed capacitance, minimum 7, maximum 10 mmf, should not differ from any other resistor by more than 2 mmf.

(B) For high voltage paper capacitors, the 0.004-inch thick Kraft paper, which constitutes the dielectric, was selected from the most promising mill lots which the manufacturers had to offer. This selection was based on the results obtained from tests that involve examination for porosity, conducting material and conductivity of water extractions. These tests were followed by the winding and impregnation in Halowax of test capacitors. The test capacitors were then subjected to a direct voltage endurance test at 266 degrees F for 24 hours.

Samples of prospective lots of paper, which have passed the above test, were then used to wind another group of test capacitors that were subsequently impregnated with Aroclor and sealed. 1,500-volt dc was then applied to the capacitors at 203° F for 500 hours. In case of failure, a second sampling was permitted.

After the foregoing tests had been passed, the supplier providing the particular mill lot was authorized to slit the paper. Upon receipt, six special capacitors were wound, using a group of six rolls of the paper being qualified. These capacitors were then impregnated, checked for dielectric strength at 3,000-volt dc, and measured for capacitance and insulation resistance. The capacitors were then given an accelerated life test at 2,000-volt dc, temperature 150° F, for 25 days. Each lot of six satisfactory test capacitors qualified six rolls of paper for use.

Product capacitors were then wound from approved paper, and the dry units checked for dielectric strength at 300-volt dc. Capacitance

was checked and units were then assembled into cans and ceramic covers soldered in place. Assemblies were pressurized with air, through a hole provided for the purpose, while the assembly was immersed in hot water to determine if leaks were present. Capacitors were then baked, vacuum dried, impregnated, pressurized with nitrogen, and sealed off. The completely sealed units were then placed in a vacuum chamber at a temperature of 150° F, 2 mm. mercury, for 3 hours to check for oil leaks. Capacitance was rechecked and insulation resistance measured.

After seven days, capacitors were unsealed to replenish the nitrogen that had been absorbed by the oil, resealed and again vacuum leak tested. An X-ray examination was then made of each individual unit to verify internal mechanical conditions. Capacitors were then placed in a temperature chamber and given the following treatment for one cycle:

16 hours at 150°F; 8 hours at 75°F; 16 hours at 0°F; 8 hours at 75°F.

At the end of ten days, or 5 cycles, the insulation resistance and conductance was measured and a norm established for capacitance.

Capacitors were then recycled for ten days, and, if the capacitance had not changed more than 0.1 per cent, they were satisfactory to place on production life test. If the foregoing conditions had not been met, the capacitors were recycled for periods of ten days until stabilized.

At that time, 10 per cent of the capacitors in every production lot were placed on "Sampling Life Test", which consisted of applying 4,000-volt dc in a temperature of 150°F for 25 days. At the same time, the balance of the capacitors in the lot were placed on production life test at 3,000-volt dc in a temperature of 42°F for 26 weeks. At the end of this time, the insulation resistance was measured and the capacitance checked at 75°F and at 39°F. The difference in capacitance at the two temperatures could not exceed +0.001, −0.005 mf, and the total capacitance could not exceed maximum 0.3726, minimum 0.3674 mf. The capacitance from start to finish of the life test could not have changed more than plus or minus 0.1 per cent.

If all of the preceding requirements had been satisfied, the particular lot of capacitors described was considered satisfactory for use.

The foregoing examples are typical of the procedures evolved for insuring, to the greatest degree possible, the long, trouble-free life of all apparatus used in the repeater.

Radioisotope Test

There were many new and involved tests which were developed and applied to the manufacture of repeaters. One of the most unique is the use of a radioisotope for the detection of leaks under hydraulic pressure.

The initial closure operations consisted of brazing into each end of the repeater housing a Kovar-to-glass seal. These seals are equipped with small diameter nickel tubulations which were used to flush and pressurize the repeaters with nitrogen. After these operations had been performed, one of the tubulations was pinchwelded, overbrazed and coiled down into the seal cavity. The repeater was then placed in a pressure cylinder with the open tubulation extending through and sealed to the test cylinder. A mass spectrometer was then attached to the tubulation and the test cylinder pressurized with helium at 10,000 psi. At the conclusion of this test the repeater was removed from the test eylinder and, after breaking the desiecator diaphragm, the remaining open tubulation was pinchwelded and overbrazed. At this point, it became necessary to determine whether the final pinchweld and overhrazing would leak under pressure.

Since there was no longer any means of access to the inside of the repcater, all testing bad to be done from the outside. This was accomplished by filling the glass seal with a solution of radioisotope cesium 134, which was retained by a fixture. The repeater was then placed in a test cylinder and hydraulic pressure applied, which was transmitted to the radioisotope in the fixture. After 60 hours under pressure, the repeater was removed from the cylinder and the seal drained and washed. An examination was then made with a Geiger counter to determine if any of the isotope had entered the final weld.

The washing procedure, after application of the isotope solution, involved some sixty operations with precise timing. In the case of the repeater at the rubber seal stage where both ends were tested, it was desirable that these operations be performed concurrently. This was accomplished by recording the entire process on magnetic tape which, when played back, furnished detailed instructions and exact timing.

RAW MATERIAL INSPECTION

As might be expected, raw materials used in the project were very carefully examined and nothing left to chance. Every individual har, rod, sheet, tube, bottle or can of materials was given a serial number and a sample taken from each and similarly identified. Each sample was then given a complete chemical and physical analysis before each eorresponding piece of material was eertified and released for processing. In many cases, the cost of inspection far exceeded the cost of the material. However, the discrepancies revealed and the assurance provided, more than justify the expense.

Detailed records of all raw material inspection were compiled and furnished to the responsible raw material engineer who examined them,

critically, as an additional precaution before the material was released to the shop.

INSPECTION RECORDS

To eliminate, as much as possible, the human element in providing assurance that all prescribed operations had been performed satisfactorily, inspected properly and the results recorded, means were established to compile a complete history of the product concurrent with manufacture. This was accomplished through the provision of permanent data books of semilooseleaf design, which require a special machine for removing or inserting pages.

Each of these books covered a portion of the work involved in producing a piece of apparatus and contained a sequential list of pertinent operations and requirements prescribed in the manufacturing process specifications. Space was provided, adjacent to the recorded information, for both the operator and inspector to affix their initials and the data. A reference page in the front of each book identified the initials with the employees' names. All apparatus was serially numbered and the data were identified accordingly. If a unit was rejected, that serial number was not reused.

These data books, in addition to establishing a complete record of manufacture, provided a definite psychological advantage in that people were naturally more attentive to their work when required to sign for responsibility.

QUALITY ACCURACY

As pointed out previously, every precaution was exercised in selecting and training inspection personnel assigned to the project. However, it was realized at the outset that human beings are not infallible and that insurance, to the greatest degree possible, would have to be provided against the probability of errors in observation and jugment. Quality accuracy evaluation procedures were, therefore, established for determining the accuracy of each inspector's performance.

Quality accuracy checking was performed by a staff of five Inspection Representatives and involved an examination of the work performed by inspectors to determine how accurately it was inspected. Materials which the inspector accepted and those which had been rejected were both examined.

VERIFICATION AND SUMMARY OF DATA

As an added measure of assurance as to the integrity of the product, procedures were established for verifying and summarizing the inspection records for each serially numbered component, up to an including complete repeaters.

Verification involved a complete audit of the inspection records to provide assurance that all process operations were recorded as having been performed satisfactorily, that the prescribed inspections had been made, and that the recorded results indicated that the product met all of the specified requirements. This work was performed by a group of six Inspection Representatives who had considerably experience in all phases of inspection and inspection records.

As the verification of a particular piece of apparatus proceeded, a verification report was prepared which, when completed, contained the most pertinent inspection data, such as:

(1) Recorded measurements of electrical parameters.

(2) Values calculated from measurements to determine conformance.

(3) Confirmation that all process and inspection operations had been verified.

(4) Identification (code numbers and serial or lot numbers) of materials and components entering into the product at each stage of manufacture.

The verification report usually listed the data for twenty serial numbers of a particular code of apparatus along with the specified requirements. Included, also, was a cross-reference to all the inspection data books involved so that the original data could be located easily. These verification reports were prepared for all apparatus up to and including the finally assembled and tested repeaters.

The following gives an indication of the number of items examined in the verification of one complete repeater:

Items verified in data books	17,593
Items verified on recorder charts	1,142
Calculations verified	1,580
	20,315
Number of entries on verification reports	4,070

Verification reports, in addition to presenting the pertinent recorded data, provided a "field" of twenty sets of measurements from which it was easily possible to spot a questionable variation. For example, it was the adopted practice on this project to examine, critically, any characteristic of a piece of apparatus, in a universe of twenty, which varied considerably from the rest, despite the fact that it was still within limits.

While the number of cases turned up in the verification process which have resulted in rejection of product are relatively few, we believe that the added insurance provided, and the psychological value obtained, considerably outweigh the cost.